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# Reliability Analysis of the
# Gradual Degradation of Semiconductor Devices

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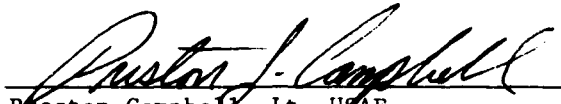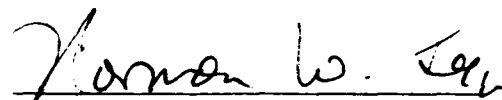
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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

A review of the recent results on accelerated aging of both power and low-noise GaAs FETs indicates that the major failure mode occurs by gradual deterioration and not by the usually (implicitly) assumed catastrophic device failure. It is shown that assuming catastrophic degradation when devices actually fail gradually can lead to incorrect device reliability predictions. The analysis of accelerated aging results for a gradual degradation failure mode is indicated.

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# I.  INTRODUCTION

The reliability of semiconductor devices can only be estimated efficiently
on the basis of life test data to the extent that the assumptions used in the
analysis are correct.  It is quite common to perform a reliability analysis on
life test results of power GaAs FETs assuming an arbitrary failure definition
such as a 1.0 dB decrease in output power.  If the devices have not degraded
by 1.0 dB we assume that no degradation occurred, whereas if the decrease in
output power is 1.0 dB or greater we consider the device completely inopera-
tive.  The device lifetime would be defined as the time required to degrade by
1.0 dB.  The use of an arbitrary failure definition is correct when the de-
vices fail by a pure catastrophic mode.  When devices fail catastrophically
the failure definition is no longer arbitrary, because the lifetime is inde-
pendent of the failure definition.  For example, with a pure catastrophic
failure mode the times required to reach -0.5 dB or -1.0 dB are equal.  When
the devices deteriorate gradually, which appears to be the situation with
properly produced and screened power GaAs FETs, the use of an arbitrary
failure definition (or the equivalent assumption of a pure catastrophic
failure mode) is incorrect and can result in a faulty prediction of device
reliability.

Experience has shown that semiconductor devices can fail in one of two
general modes: catastrophic or gradual degradation.  The catastrophic failure
mode proceeds suddenly from an operating to a failed state.  With gradual
degradation the device performance has a generally decreasing behavior.  The
catastrophic failure is from a non-degraded operating state to a completely

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inoperative state, such as a shorted or opened device. Catastrophic failure usually results in electrical overstress which causes excessive heating and fusing of the internal structure of the device. With gradual degradation, performance is gradually decreased and the total amount of deterioration is much less than with catastrophic failure. For example, the output power of a GaAs FET might be reduced by 1.0 dB after many years of operation.

Accelerated aging tests of power GaAs FETs have shown both types of failures. With improved processing and screening, the catastrophic failure mode has been nearly eliminated and gradual degradation is common. The occurrence of a catastrophic failure is usually viewed as a test failure (e.g., voltage transient), operator mishandling, or improper screening.

Because the major failure mode is gradual degradation, it is important that this information is properly handled in reliability analysis. Unfortunately, the opposite is true -- we treat all failures as if they were catastrophic, although in actual usage the devices we are interested in gracefully degrade. The reason for this situation is simple to rationalize. It is much easier to mathematically analyze catastrophic degradation. With catastrophic failure the device can be in only two states --- fully operating or non-operative.

Not only is catastrophic failure easier to treat, but there is strong precedent for this assumption. The common household light bulb fails catastrophically as do many other items in everyday use. Some types of semiconductor devices show no degradation and then catastrophically fail. This appears to be common with silicon IMPATT diodes and with TWTAs.

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Gradual degradation is also familiar. The normal human aging process is one of gradual degradation, and it is this pattern that properly screened and handled power GaAs FETs follow.

Although gradual deterioration is common, to the author's knowledge all reliability texts (e.g., Refs. 1 and 2) perform their analysis assuming that all failures are catastrophic. Mil-HDBK-217C appears to be constructed on the principle that all failures are catastrophic. This reliability handbook cannot be used, for instance, to find the time for a power bipolar to experience a gain degradation of 1 or 2 dB.

Behavior similar to gradual degradation is treated in statistics under the heading of linear models or linear statistical models.[3,4] We have not used this material in this report.

Assuming catastrophic failure when graceful degradation occurs is not always a conservative position, because of the arbitrary assumption of when catastrophic failure occurs. Neglecting the graceful degradation that occurs before the devices reach some arbitrary failure criterion can result in poor estimates of amplifier lifetime.

The use of an arbitrary failure definition when gradual degradation occurs may not directly relate to our prime interest — maximizing utilization of resources. For the purpose of this discussion, it is assumed that our primary objective is to minimize the cost associated with the employment of space-borne solid-state amplifiers. We believe that this problem is most effectively treated by means of a personalistic probability approach[5] or equivalently from a "businessman's viewpoint".[6,7] Why should a device still be good when it has degraded by 0.95 dB, but suddenly becomes useless when it

degrades another 0.05 dB?  How much more should we be willing to pay for
devices associated with a 0.5 dB failure criterion than for devices with a
1.0 dB failure criterion?  From a "businessman's viewpoint" a better approach
than using an arbitrary failure criterion would be to assign a loss schedule
to cover any amount of degradation.

In the following section is provided a general overview of the statis-
tical analysis of reliability test results with particular attention to the
analysis of accelerated aging results.  The assumptions commonly employed in
this analysis are listed and those of special importance to our present dis-
cussion highlighted.  The analysis in Section II is based on the assumption of
catastrophic failure. Although the detection and elimination of early failures
is very important in achieving reliable devices, it is not of immediate
interest in this report.

Using the above review as a foundation, we then review the life test
results on power GaAs FETs that have been published in the open literature.
Results on the reliability of low noise GaAs FETs, which are of direct inter-
est, are also discussed.  This review demonstrates that gradual degradation is
the major failure mode, although little information on the detailed temporal
and temperature dependence of gradual degradation exists.  It is probable that
gradual degradation is not experimentally characterized in detail because of a
belief that defining an arbitrary failure level is sufficient to permit an
efficient reliability estimation.

Because detailed characterization of gradual degradation is not available
we will analyze the reliability of devices that fail gradually, assuming some
general failure characteristics.  We first consider the idealized situation of

many units aged at the operating temperature, which permits us to determine the failure probability density function with great accuracy. On the basis of this aging information, we estimate the reliability of a single unaged device assuming a catastrophic mode and then gradual degradation. This treatment is then extended to a system consisting of a string of devices. A large difference is shown between the reliability estimates derived from assuming catastrophic and gradual degradation.

The next section discusses analysis of accelerated aging results. This treatment is similar to our previous analysis of accelerated aging assuming a catastrophic model. In this treatment we first modify our system loss formula and then proceed to the actual analysis.

## II.  ANALYSIS OF ACCELERATED AGING RESULTS
## ASSUMING CATASTROPHIC DEGRADATION

The efficiency of estimating the reliability of semiconductor devices is strongly dependent on the correctness of the assumed failure probability density function (pdf).  The following assumptions are usually made about the failure pdf:

1.  The failure mode is catastrophic.

2.  The failure time at a constant temperature and applied electrical stress is a single log normal pdf.

3.  The logarithmic variance is independent of temperature.

4.  The median failure time follows an Arrhenius dependence expressed as

$$\tau_M = \tau_o \exp \left(\frac{\Delta E}{RT}\right)$$

To perform an error analysis of accelerated aging results the following additional assumptions are suggested in our analysis of accelerated aging.[8]

5.  The system loss due to the failure of the i-device is best described as

$$\Delta L_i = \int_o^{t_s} R_i(t) \, F_i(t) \, dt$$

where $F_i(t)$ is the cumulative failure function, cff, and $R_i(t)$ is the loss rate for the failure of the i-device.  The integration is performed over the system life from zero to $t_s$.

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6. The total system loss is the sum of the individual device losses.[*]

7. The best estimate of the cumulative failure function is the Student-t analysis.

Each of the above assumptions can be challenged. For example the assumption of only a main population (assumption 2) is incorrect because early failures are known to occur, and in actual practice the effective failure rate is often actually determined by early failures. The assumption of one activation energy (assumption 4) also deserves careful attention. Our interest here is the implication of assumption 1: that all failures are catastrophic.

The normal accelerated aging test is conducted as follows. A failure definition is arbitrarily assumed, and devices are stressed at several elevated temperatures. For power GaAs FETs the usual failure definition is a decrease of 1 dB in output power at the 1 dB compression point. The output power is usually measured at a suitable normal operating temperature. The devices are then stressed at several elevated temperatures, and their performance at the normal operating temperature is periodically measured. The estimated time at the accelerated temperature required for the device to degrade to an output power of −1.0 dB is estimated and referred to as the failure time.

When all devices placed on the accelerated stress test exceed the arbitrary failure definition, complete failure data result. If the test is terminated before complete failure data are realized, censored data are

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[*]This assumption is examined in detail in Ref. 9.

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obtained, which are more difficult to analyze.[10]  In the case of complete

failure data, we have for each device placed on test the accelerated

temperature and the failure time at this temperature.  These data are

conveniently represented as follows:

| Device | Temperature | Failure Time |
|--------|-------------|--------------|
| 1 | $T_1$ | $\tau_1$ |
| 2 | $T_2$ | $\tau_2$ |
| . | | |
| . | | |
| . | | |
| n | $T_n$ | $\tau_n$ |

and are easily analyzed by simple linear regression.  Since we have assumed a

log normal/Arrhenius activation process, it is convenient to convert the above

failure data to

$$z_i = (kT_i)^{-1}$$

where $T_i$ is the accelerated temperature in Kelvin, k is Boltzmann's constant,

and

$$x_i = \ln \tau_i$$

With the above transformation we estimate the parameter characterizing the

failure pdf as

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$$\overline{\Delta E} = \frac{\sum (x_i - \overline{x})(z_i - \overline{z})}{\sum (z_i - \overline{z})^2}$$

$$\overline{\ln \tau_o} = \overline{x} - \overline{\Delta E}\, \overline{z}$$

$$\hat{\sigma}^2 = \frac{1}{n-2} \sum (x_i - \overline{\ln \tau_o} - \overline{\Delta E}\, z_i)^2$$

where

$$\overline{x} = \frac{1}{n} \sum x_i$$

and

$$\overline{z} = \frac{1}{n} \sum z_i$$

With the above estimated failure pdf parameters, we can estimate the median lifetime at the normal operating temperature as

$$\ln \tau_M = \overline{\ln \tau_o} + \overline{\Delta E}\, z_N$$

where $z_N$ refers to the normal operating temperature. Many accelerated stress tests are only analyzed to give the median lifetime and standard deviation at the operating temperature. This procedure is incorrect because we are not directly interested in the device's median lifetime but in the probability that the device will fail during operation; i.e., we are interested in determining the failure probability of the $n + 1$ device as a function of operating time from the accelerated aging results of a sample of n devices. The cumulative failure function versus normal operating time is needed to

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estimate the reliability loss. According to our seventh assumption the Student-t analysis is the most effective way to estimate the cumulative failure function of the n + 1 device based on the results of an accelerated aging test consisting of a sample of n failed devices.

The Student-t analysis gives the estimated cumulative failure function, $\overline{F(t)}$, as

$$P\left\{\ln t \leqslant \overline{\ln\tau_o} + \overline{\Delta E}\, z_N - t_{n-2}\left[\overline{F(t)}\right]\, \hat{\sigma}\, (\sigma_u/\sigma)\right\} = \overline{F(t)}$$

where

$t$ = operating time at normal temperature for the n + 1 (i.e., unaged) device

$z_N$ = $(kT_N)^{-1}$

$T_N$ = normal operationing temperature

$t_{n-2}\left[\overline{F(t)}\right]$ = Student-t distribution with n − 2 degrees of freedom at probability $\overline{F(t)}$

$\sigma_u/\sigma$ = statistical efficiency of the accelerated aging test

$n$ = accelerated aging sample size.

The statistical efficiency is determined from the accelerated aging results as*

$$\left(\sigma_u/\sigma\right)^2 = 1 + \frac{z_N^{\,2} - 2z_N\overline{z} + \Sigma\, z_i^2}{\Sigma(z_i - \overline{z})^2}$$

*This equation was misprinted in TR-0081(6930-02)-01, but this error was not propagated in the remainder of the report.

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## III. REVIEW OF EXPERIMENTAL POWER GaAs FET RELIABILITY RESULTS

One of the earliest reported results on the reliability of power GaAs FETs was by Drukier and Silcox,[11] who investigated devices produced by Microwave Semiconductor Corp. (MSC). They employed a failure definition of a 1 dB output power change and dc biased their devices at several channel temperatures ranging from 280 to 150°C. The average failure times at the various channel temperatures were used to determine the extrapolated average failure time at 125°C. They estimated an activation energy of 1.85 eV and an extrapolated average failure time at 125°C of approximately $2 \times 10^6$ hr. Most of their devices gradually degraded to the -1 dB failure criterion. Even those devices that reached the -1.0 dB failure level by catastrophic means were believed to fail because of spurious oscillations. These investigators believed that these catastrophic failures represented test mishaps rather than true device failures.

Although the majority of their devices gradually degraded, Drukier and Silcox provide no detail information to characterize the temporal or temperature dependence of this gradual degradation, except the time the device took at the various elevated temperatures to reach -1.0 dB.

Cohen and MacPherson[12] also examined MSC power GaAs FETs. Although they performed accelerated temperature stress tests on a much smaller number of devices than Drukier and Silcox, they applied rf during aging to better approximate the conditions a device experiences in actual operation. They reported an average lifetime extrapolated to 125°C, similar to the estimation of Drukier and Silcox. Although the failures were equally divided between

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catastrophic and gradual degradation, Cohen and MacPherson concluded that both types of failures resulted in a similar extrapolated lifetime. No detail information was provided on the development of gradual degradation. Similar results on the split between catastrophic and gradual degradation are presented by the same group for aluminum gate power GaAs FETs.[13,14]

A reliability study comparing aluminum and gold-based gates was provided by Benedek and Hewitt,[15] who reported the primary failure mode to be the gradual degradation of $I_{DSS}$. The gate metal interaction with the active channel is suggested to be the cause of the $I_{DSS}$ degradation. Benedek and Hewitt also indicate that the gradual degradation of the low-field channel resistance is not caused by an increase in contact resistance but is directly related to the gate-active channel interaction.

Although Benedek and Hewitt indicate that the gradual degradation follows a log normal pdf and estimate a logarithmic standard deviation of $\sigma = 0.7$,[*] their failure criterion is not clearly stated. They provide selected information on the temporal development of the gradual decrease of $I_{DSS}$. Their curves indicate a delay before the start of gradual degradation.

Bell Laboratories have performed extensive reliability stress testing of their in-house fabricated devices.[16-18] Their initial device degraded catastrophically (burnout) but with improved fabricating techniques they have improved their device reliability and now mainly experience only gradual degradation. In stress testing of 270 devices at elevated temperatures, only one device failed catastrophically, whereas the others experienced a slow

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[*]Throughout this report we will use the convention that $\sigma$ is operationally defined as $\ln(\tau_M/\tau_{16})$.

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deterioration. A close correlation is indicated between gradual degradation of $I_{DSS}$ and output power. The amount of degradation is independent of rf at reasonable drive levels.

The standard deviation of $I_{DSS}$ and $P_{out}$ during aging was 0.02-0.04. Unfortunately Bell Laboratories did not state whether this was a logarithmic or linear standard deviation. Their temporal development of gradual degradation indicates a delay after which the devices degrade as the log of operating time.

Selecting a failure criterion of a 5% decrease in output power (i.e., approximately -0.22 dB degradation in $P_{out}$) a median lifetime of greater than $10^8$ hr at 110°C was estimated with an associated logarithmic standard deviation of approximately 0.4.

References 19 through 21 deal with low-noise devices that have been included in this review because they have a similar (but reduced area) device structure. These low-noise GaAs FETs, like the larger active area power devices, mainly degrade in a gradual manner and not by catastrophic failure. Irie et al.[19] report that the main failure mode results from the decrease in the specific drain current, i.e., the drain current at $V_D$ = 0.5 V and $V_G$ = 0 V. Under these voltage conditions the active channel is in the unsaturated region and the drain current is strongly dependent on the device parasitic contact resistances. The decrease in the specific drain current observed during elevated temperature aging is attributed to an increase in the contact resistance. This conclusion is different from the conclusion suggested in Refs. 15 and 18. No information on the failure pdf is provided, and the data on the time evolution of gradual degradation do not allow the temporal development of gradual degradation to be established confidently.

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Mizuishi et al.[20] report that the major failure mode in the low-noise devices they examined was the gradual degradation of the specific drain current, which they related to the increase in the source and drain contact resistance. They report that the fraction drain conductance (i.e., $I_D/V_D$ at $V_D = 1.0$ V and $V_G = 0$ V) decreased as

$$\frac{G(t)}{G(o)} = 1 - (bt)^{1/2}$$

where $G(o)$ is the initial value and $G(t)$ is the low field conductance after aging for t hours. They also presented results on the aging temperature dependence, from which they suggested that this coefficient, b, follows an activation process similar to that of solid-state diffusion, i.e.,

$$b = D_o \exp(-\frac{\Delta E}{kT})$$

An extensive reliability study of Bell Laboratories low-noise devices was undertaken by Irvin and Loya.[21] They found that high-temperature aging under dc bias resulted in the gradual degradation of the rf performance of the device. With a failure definition of 0.2 dB increase in noise figure or 0.8 dB decrease in gain, they found that the cumulative failure approximated a log normal with $\sigma = 1.3$. They did not observe a close correlation between the rf degradation and the charge in the device dc characteristics.

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# IV. ILLUSTRATIVE ANALYSIS OF GRADUAL DEGRADATION

In this section we use the artificial results presented in Fig. 1 to demonstrate the importance of correctly treating gradual degradation. A large number of devices are placed on test at the same channel temperature at which they will be used in normal operation. Their power gain is measured at various times and, because of the large sample size, we achieve a very accurate estimate of the failure pdf.

According to the results shown in Fig. 1., the median time $\tau_M$ for the power gain to be reduced to $G(t)$ is a linear function of time expressed as

$$\left[G(t)/G(o)\right]_M \equiv g(t) = 1 - \alpha\tau_M$$

where $G(o)$ = initial power gain and

$$\alpha = 9.5 \times 10^{-7} \ (hr)^{-1}$$

We further assume that not only is the failure time at any level of gain degradation log normal but also that the logarithmic standard deviation of these failure times is constant. In particular we assume:

$$\sigma = \ln\left(\tau_M/\tau_{16}\right) = 0.25$$

at all levels of gain degradation. As indicated in Fig. 1, the scatter in the failure times (on a linear time scale) is a linear function of degradation or equivalently operating time.
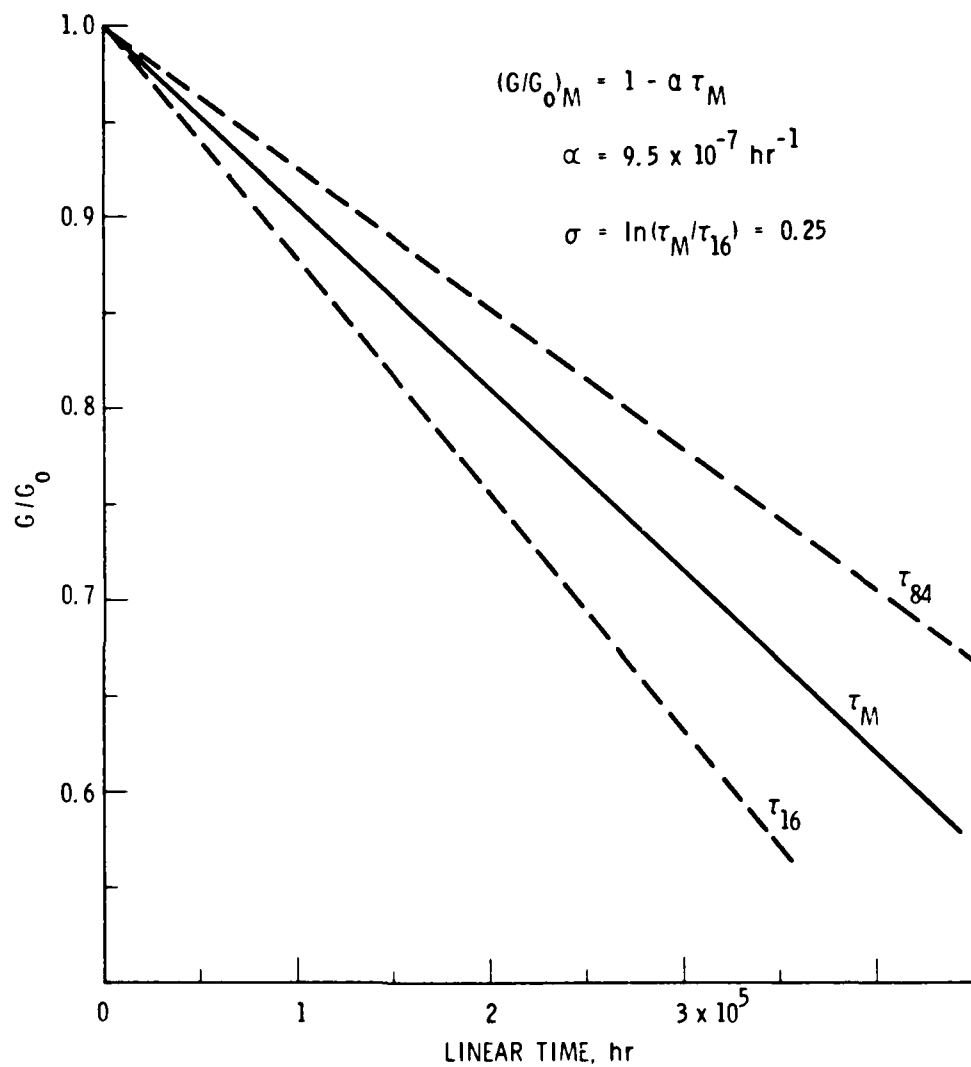
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$$(G/G_0)_M = 1 - \alpha \tau_M$$

$$\alpha = 9.5 \times 10^{-7} \ hr^{-1}$$

$$\sigma = \ln(\tau_M/\tau_{16}) = 0.25$$

Fig. 1. Schematic Illustration of the Results
of an Artificial Aging Test

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On the basis of the above failure conditions, we present the cumulative failure times at various levels of gain degradation in Fig. 2. For example, the median failure time at the -1 dB level is $2.16 \times 10^5$ hr according to both Figs. 1 and 2. The probability of a device operated for $10^5$ hr reaching the -1 dB degradation level is 0.1%.

With an arbitrary failure definition we would use only one of the curves presented in Fig. 2. For example, if our failure criterion is a -1.0 dB or greater decrease in gain we would use the curve in Fig. 2, which corresponds to a gain decrease of -1.0 dB. With this arbitrary failure criterion, we would characterize the reliability of an unstressed device from the same lot whose aging results are shown in Fig. 1 as having a 0.1% probability of not operating at $10^5$ hr. The data in Fig. 2 will now be examined without arbitrarily assuming a given failure level. We seek to characterize the expected output power degradation at $10^5$ hr with more precision than has been done previously.

On the basis of the data in Fig. 2, we constructed the cumulative distribution of power loss at $10^5$ hr in Fig. 3. The results in Fig. 3 are the same results presented in Fig. 2 at t = $10^5$ hr. Instead of just stating the probability of reaching one level of degradation, as we do when using an arbitrary failure criterion, the probabilities of reaching various levels of degradation are indicated. For example, the probability of reaching -0.6 dB at $10^5$ hr is approximately 10%.

With a catastrophic failure mode we are only interested in one cff — the distribution of failure time. When devices fail gradually there are two distributions of interest: the distributions of failure times to reach various
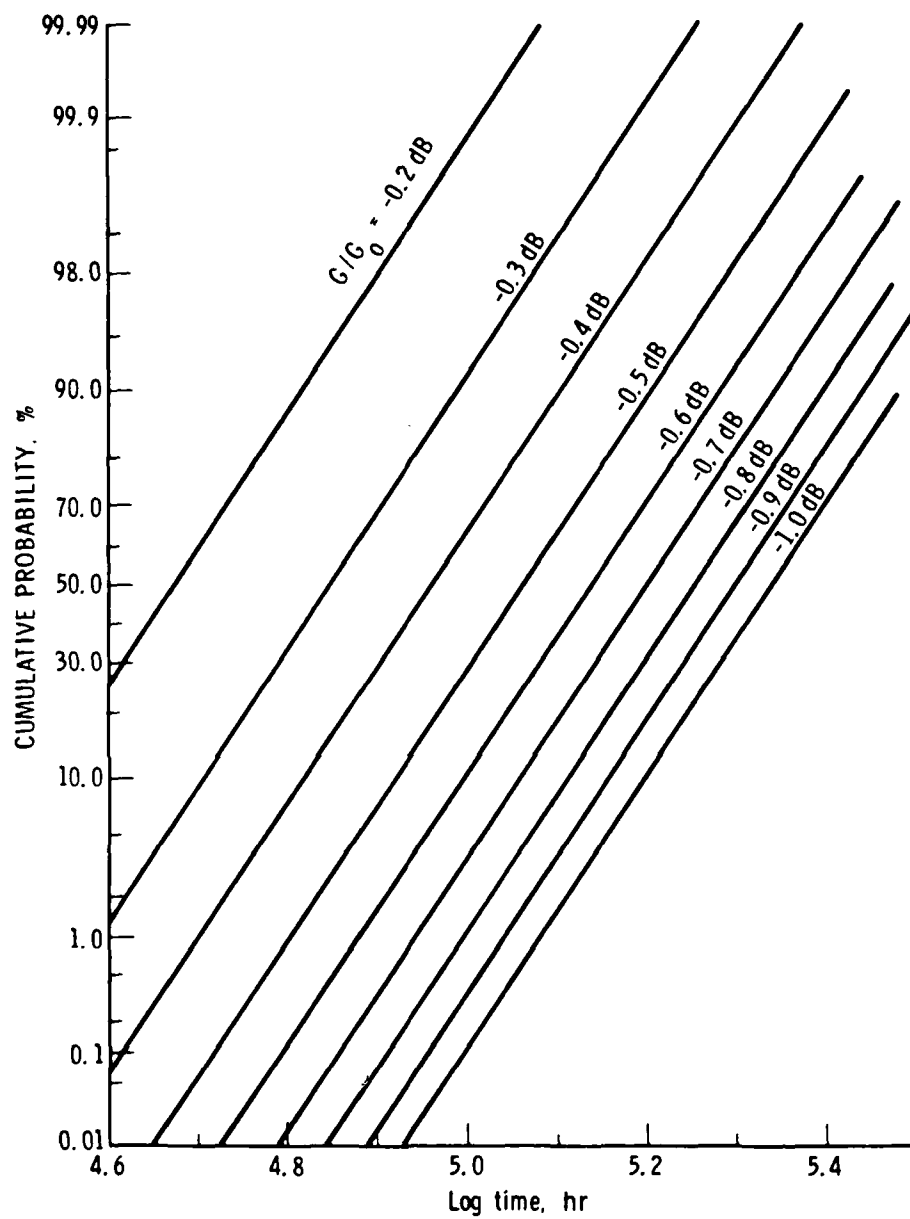
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Fig. 2. Cumulative Distribution of the Log of Failure
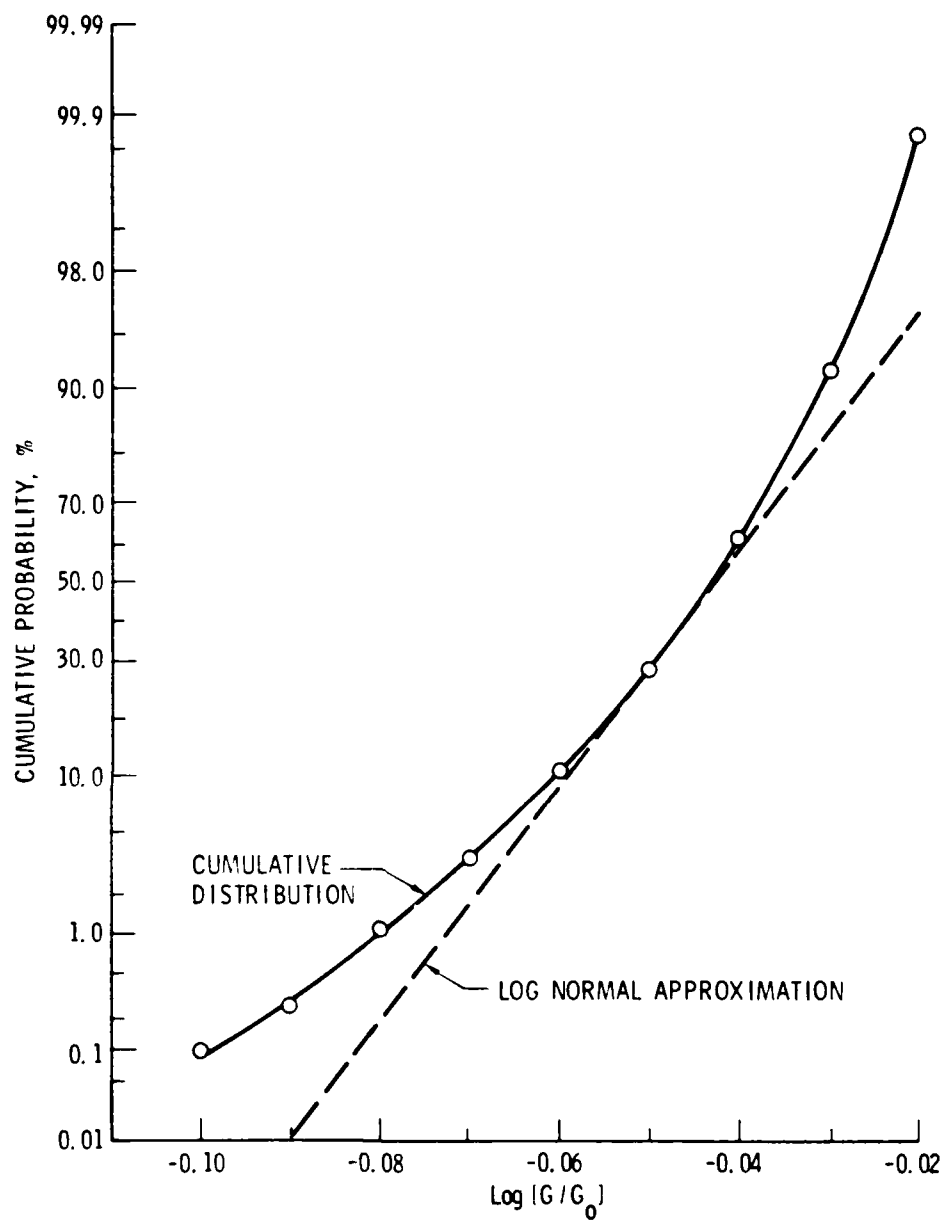Times at Various Levels of Gain Degradation

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Fig. 3.  Cumulative Distribution of Log $[G/G_0]$ at $10^5$ Hr

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levels of degradation and the distribution of gain degradation at various times. Although the failure time cff is log normal in the present case, the cumulative distribution of the relative gain degradation at a given time shown in Fig. 3 is not log normal. The logarithmic standard deviation of gain degradation at a given time can be operationally written as

$$\sigma(16\%) = \ln \left[ g(t_s)_M / g(t_s)_{16} \right]$$

where $g(t_s)_M$ and $g(t_s)_{16}$ are the fractional gain degradation evaluated at $t = t_s$ for the median and 16% values. Since

$$g(t_s)_M = 1 - \alpha t_s$$

and

$$g(t_s)_{16} = 1 - \alpha t_s e^{\sigma}$$

(where $\sigma$ is the constant standard deviation of the failure times cff, which in the present case is assumed to be 0.25), we have

$$\sigma(16\%) = \ln \frac{1 - \alpha t_s}{1 - \alpha t_s e^{\sigma}}$$

proving that $\sigma(16\%)$ is not a constant but is dependent on operation time. Now consider the similarly defined

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$$\sigma(84\%) = \ln\left[g(t_s)_{84}/\ g(t_s)_M\right]$$

$$= \ln\left[\frac{1 - \alpha\, t_s e^{\sigma}}{1 - \alpha t_s}\right]$$

which is not equal to $\sigma(16\%)$, proving that the cumulative distribution of gain degradation at a constant time is not log normal if the time required to reach a given level of gain degradation is log normal.

If instead of plotting the cumulative distribution of log $[G/G_0]$ at a constant operating time we consider log $[1 - g]$, a log normal pdf would be obtained as indicated in Fig. 4. We can establish that this is true analytically as follows

$$\sigma(16\%) = \ln\left[\frac{1 - g(t_s)_M}{1 - g(t_s)_{16}}\right]$$

$$= \ln\left[\frac{\alpha t_s}{\alpha t_s e^{\sigma}}\right]$$

$$= -\sigma \equiv -\ln\left[\tau_M/\tau_{16}\right]$$

which is independent of operating time.

The negative sign results because $[1 - g(t)]$ and therefore log $[1 - g(t)]$ at a given operating time increases with decreasing cumulative probability as shown in Fig. 4. Repeating this for the 84% point we write

$$\sigma(84\%) = \ln\left[\frac{1 - g(t_s)_{84}}{1 - g(t_s)_M}\right]$$

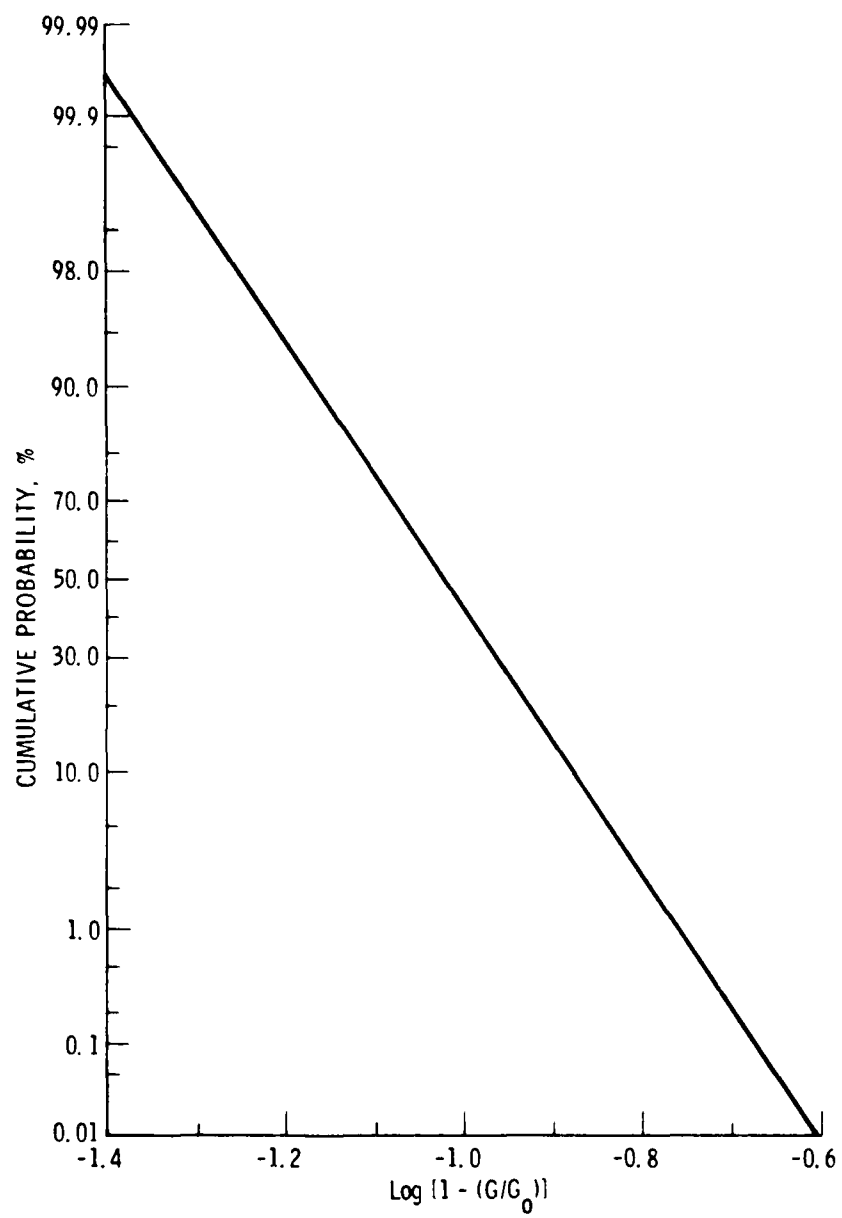$$= -\sigma \equiv -\ln\left[\tau_{84}/\tau_M\right]$$

Fig. 4. Cumulative Distribution of Log $\left[1 - \left(G/G_0\right)\right]$

or

$$\sigma(16\%) = \sigma(84\%)$$

as required for a log normal pdf.  Extending this argument to any other cumulative percentages shows that log $[1 - g(t)]$ at a given time is log normal and the logarithmic standard deviation is independent of time.

We have replotted the cumulative gain distribution at $10^5$ hr in Fig. 5a in a form a businessman might better appreciate.  In this presentation we show the probability of having a relative output power below a given level after operating for $10^5$ hr.  The shaded area represents power loss of approximately 10% at $t = 10^5$ hr.

To emphasize the difference between our previous way of characterizing reliability, we summarize the above results:

$$at \ t = 10^5 \ hr$$

Old statement:

"The probability of a device degrading by -1 dB or greater is approximately 0.1%."

New statement:

"The average power reduction is approximately 10%."

Although there is a large difference in the above two statements both are correct.  The difference between the two statements is directly due to the different methods of analyzing the aging results.
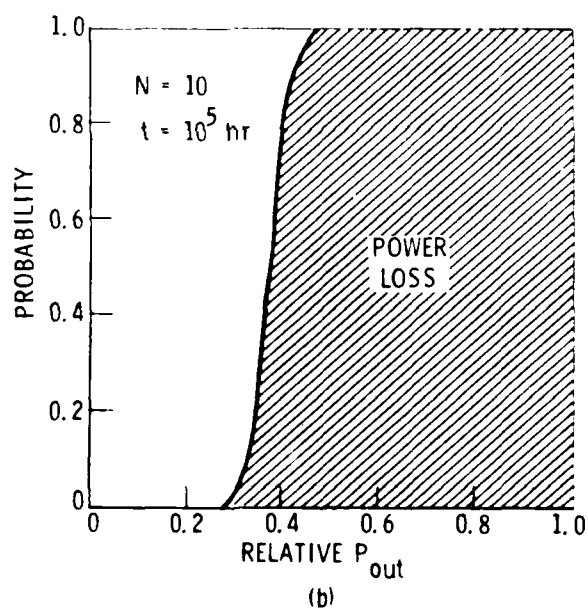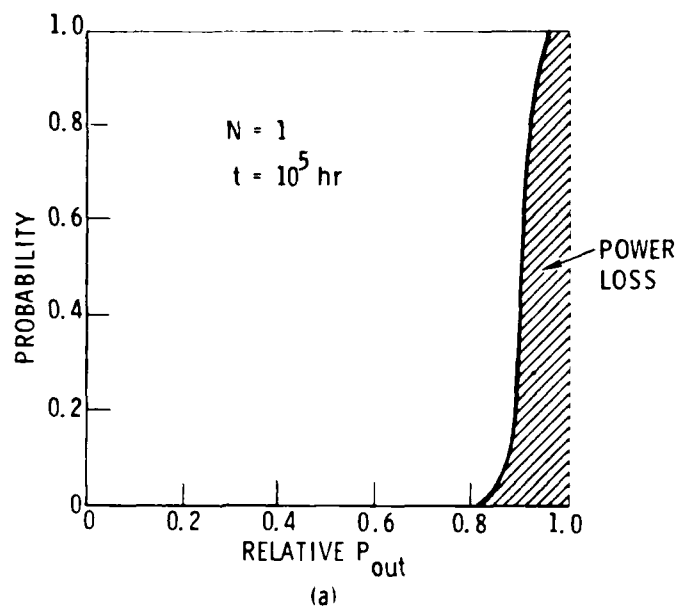
Fig. 5. "Businessman" Presentation of Gain Degradation at
$10^5$ Hr. (a) Single Device, (b) String of 10 Devices

The estimated power loss using the arbitrary -1.0 dB failure criterion is not clearly displayed in Fig. 5A because of its low probability (i.e., 0.1%). We can better display the difference between the catastrophic failure assumption and gradual degradation by increasing the standard deviation for the assumed results shown in Fig. 1. Keeping the same median gain degradation time dependence as before but using a logarithmic standard deviation of $\sigma = 1$ results in the cumulative failure time curves displayed in Fig. 6. For an arbitrary failure definition of -1.0 dB, the probability of a given unaged device reaching -1.0 dB gain degradation is now 22%. The cumulative gain degradation at $10^5$ hr is presented in Fig. 7.

The cumulative gain distribution is displayed in Fig. 8 at $10^5$ hr in a "businessman" presentation for both the arbitrary -1.0 dB failure definition and gradual degradation. The only common point on the two power loss curves is the 22% at the -1.0 dB point indicated in both curves. With the catastrophic degradation assumption there is a 22% probability of having any relative power loss from zero to unity. With gradual degradation the probability of having a given power loss decreases with the relative power loss.

We now extend our discussion to consider a string of N devices and estimate the reliability based on the cumulative gain degradation shown in Fig. 3. In this extension, the illogic of not considering gradual degradation becomes even more evident. The problem is addressed first with the standard method, and then by considering gradual degradation.

In the classical method[9] the question is asked, "Given that the failure probability of a single device being degraded to a given level is Q, what is
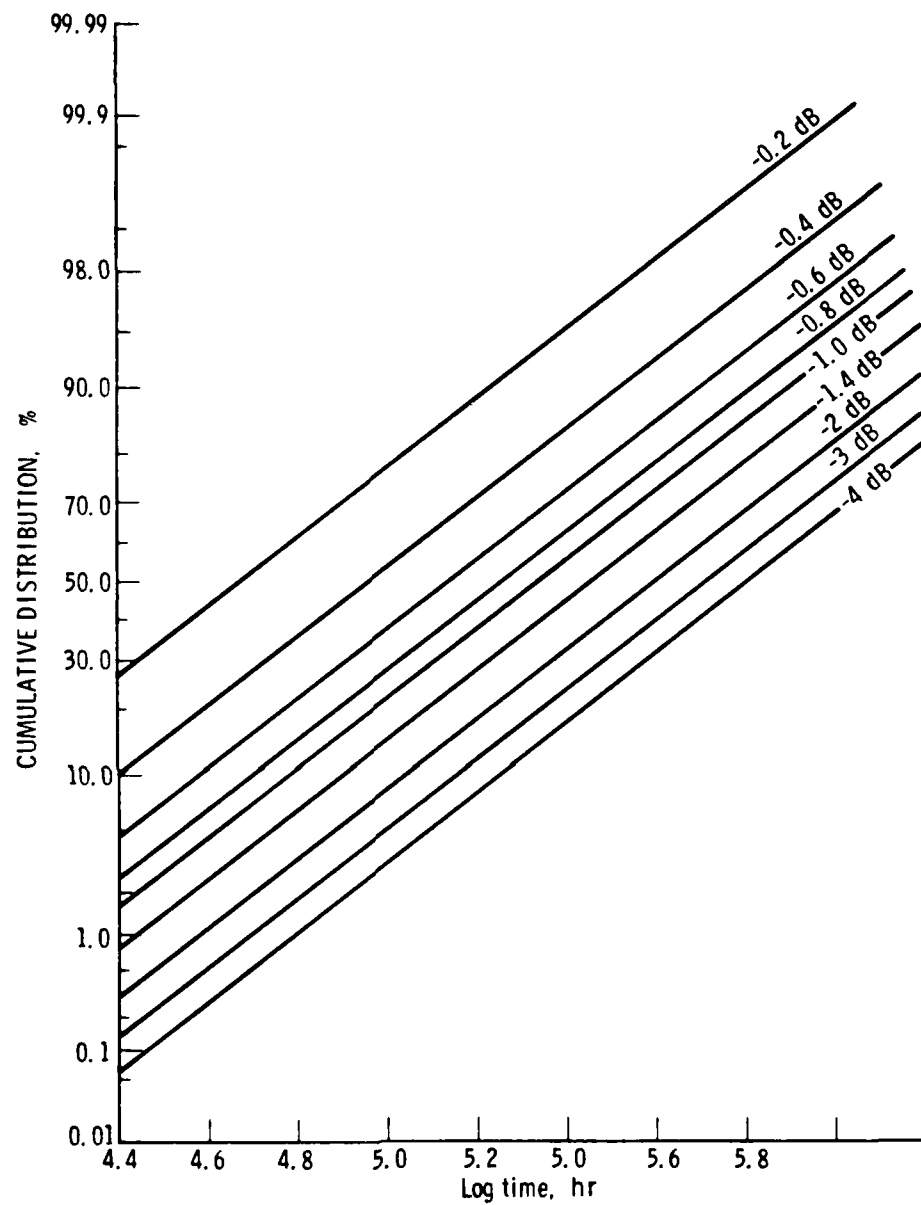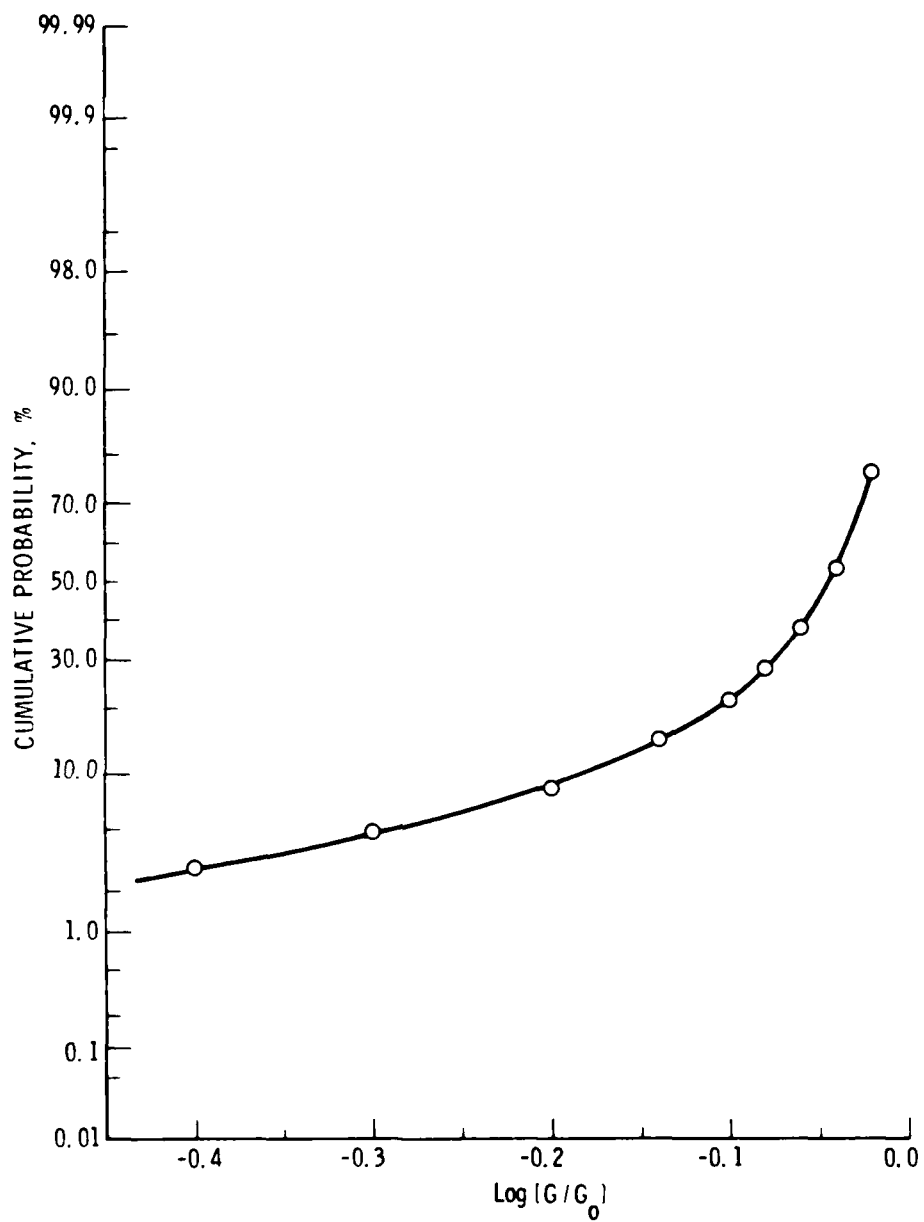
Fig. 6.   Same as Fig. 2 except σ = 1.0
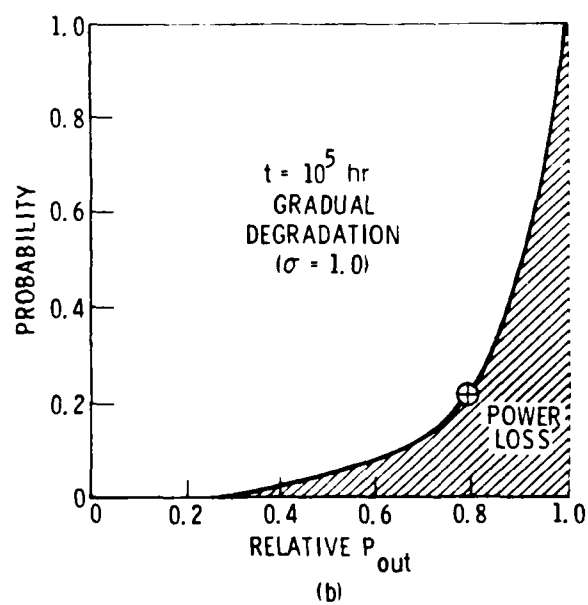
32

Fig. 7.   Same as Fig. 3 except σ = 1.0

33
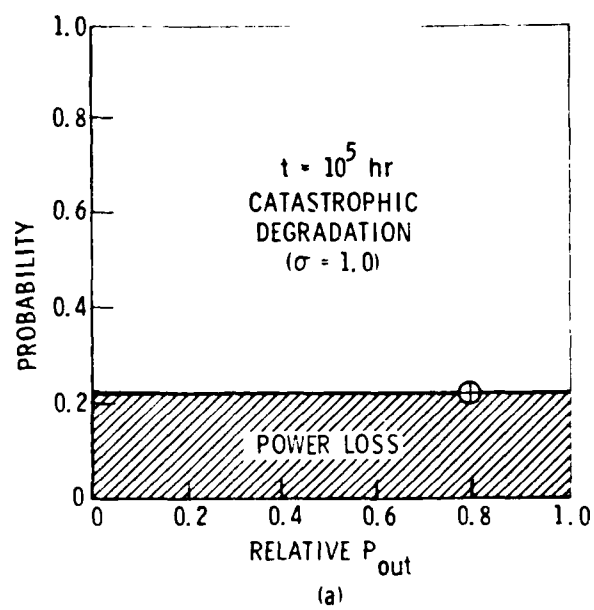
Fig. 8.  Comparison Between Catastrophic and Gradual

Degradation Employing "Businessman" Presentation

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the probability that at least one of a string of N devices will reach the failure level?" The probability of a given device not failing is:

$$R = 1 - Q$$

and the probability that none of N devices fail is:

$$R_T = (1-Q)^N$$

The required failure probability is therefore:

$$Q_T = 1 - (1-Q)^N$$

$$\approx N Q \quad \text{for} \quad Q \lll 1$$

In our first example ($\sigma = 0.25$) we had for a $-1$ dB level $Q = 0.1\%$, which gives $Q_T = 1\%$ for the probability that at least one of a string of 10 devices will have exceeded $-1$ dB.

Now consider gradual degradation. In Fig. 3, the median gain degradation at $10^5$ hr is $-0.43$ dB. With a string of N devices we would expect half to have more degradation than this median value and half to have less degradation. We can approximate the total degradation of the string by assuming that each device has the median value and write the total degradation as

$$g_T = g^N$$

or for 10 devices in series

$$g_T \approx 0.37 \ (-4.3 \text{ dB})$$

a value much greater than -1 dB. The large difference in the two conclusions in general terms can be explained as follows. The probability of a device degrading by -1.0 dB is small and therefore the probability of any one of a string of 10 devices reaching -1.0 dB is 10 times this probability for a single device and still small. On the other hand, the average gain degradation of a single device is 0.43 dB and not many devices in series are needed to greatly exceed -1.0 dB with a high probability.

Although the above analysis could be improved and a nearly exact answer obtained by employing a Monte Carlo simulation,[9] we do not consider such effort to be worthwhile because of the artificial aging results. Instead we will approximate the cumulative distribution with the log normal shown in Fig. 3. The log normal we have selected is optimistic because the actual degradation is greater than the log normal.

With a log normal we can use the self-reproductive property of a normal distribution and write the cumulative gain distribution for a string of N devices. This new cumulative gain is log normal with scale and shape parameters:

$$\mu_T = (\mu')^N$$

and

$$\sigma_T = \sqrt{N}\ \sigma'$$

where $\mu'$ and $\sigma'$ are the scale and shape parameter of the approximate log normal indicated in Fig. 3. The results are plotted on a linear scale in Fig. 5b. The total degradation using the log normal approximation is nearly equal to our handwaving results (-4.3 dB). Since the log normal was optimistic we know that the exact degradation is greater than -4.3 dB.

We once more emphasize the difference between the classical and gradual degradation analyses:

for $t = 10^5$, $\sigma = 0.25$, and $N = 10$

Old statement:

"The probability of at least one of 10 devices degrading by more than -1 dB is 1%."

New statement:

"The average power degradation of a string of 10 devices is at least -4.3 dB."

When $\sigma = 1.0$, both the catastrophic and gradual degradation analyses will indicate a near unity probability of failure for a string of 10 devices.

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Under very special device applications the catastrophic model may give an efficient prediction of device reliability. If a single device must have a definite gain for a system to function, this definite gain level can be used as the failure criterion. When devices are used where their individual degradations are cascaded (e.g., in the string of 10 devices discussed above) a single failure criterion cannot easily be employed.

Another important aspect of gradual degradation is the number of device parameters needed for measurement during the test program. The problem does not exist with catastrophic failure, in which the device either operates or does not operate. When devices fail gracefully, the situation becomes complex. To completely characterize a device or amplifier stage, both the phase and magnitude of the four scattering parameters are required. To extend this completeness to a reliability test program, the degradation of the phase and magnitude of the scattering parameters would be measured. For absolute completeness the scattering parameter could also be measured as a function of frequency. Judicious compromises must be made to keep reliability testing within reasonable bounds.

In a typical power GaAs FET reliability program, the testing is usually limited to output power degradation. Establishing the reliability of output power on individual devices will at best only be fulfilling a necessary condition for amplifier reliability, but it is not a sufficient condition. A gradual change in the output or input match could decrease the amplifier performance.

# V. ANALYSIS OF ACCELERATED GRADUAL DEGRADATION AGING RESULTS

The analysis of accelerated gradual degradation aging results discussed in this section parallels our previous analysis of accelerated aging in which we employed the catastrophic assumption.[8] By examining how one might analyze gradual degradation we hope to understand how we can profitably conduct an accelerated aging reliability evaluation test on devices that gradually deteriorate.

A basis for evaluating reliability results must be established. There are many different methods of evaluating device reliability, from individual intuition to the application of statistical decision theory.[7,22] In the present analysis, we have chosen to employ the accuracy of statistical decision theory. The main disadvantages of statistical decision theory are that it becomes mathematically formal and complex, and it is difficult to understand, apply, and disseminate. However, the effort is worthwhile because a statistical decision theory approach allows us to objectively state and evaluate our results.

In keeping with traditional decision theory, we will evaluate our device reliability in terms of a monetary loss if the devices are not reliable, or, more precisely, the probability that the devices are not reliable. For simplicity we restrict our attention to the loss caused by a decrease in the device output power because of gain deterioration. We assume that the total system lifetime can be divided into operational time periods. During each of these operational time periods we can specify a loss for the device output power degrading to a relative power gain of $g = [G(t)/G(o)]$. The loss

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schedule will be represented as $\mathscr{L}(t,g)$. The total loss between t and t + ΔL
is

$$\frac{dL}{dt} \Delta t = \Delta t \int_0^1 \frac{d\mathscr{L}(t,g)}{dg} \mathscr{F}(g|t) \, dg$$

where the integration is performed over the relative power gain from zero to
unity. In this expression $\mathscr{F}(g|t)$ is the cumulative gain cff at a specified
time into the intended mission. The cumulative distribution is to be distin-
guished from $F(t|g)$ which we will use to represent the cumulative failure time
distribution at a gain failure criterion of g. The total system loss is

$$L = \int_0^{t_s} \left(\frac{dL}{dt}\right) \, dt$$

where we integrate over the mission duration of $t_s$.

As an illustration of the application of the above loss schedule we will
apply it to the situation in which only catastrophic degradation occurs. For
catastrophic degradation we have

$$\frac{dL}{dt} \Delta t = \Delta t \, R(t) \int_0^1 \mathscr{F}(g|t) \, dg$$

where the loss rate

$$R(t) = \frac{d\mathscr{L}(t,g)}{dg}$$

has been taken out of the integral, because it is only a function of operating
time. By definition we have for catastrophic failure

$$\int_0^1 \mathscr{F}(g|t) \, dg = F(t)$$

where $F(t)$ is the catastrophic cff. The total system loss is

$$L = \int_0^{t_s} R(t) \, F(t) \, dt$$

which is the same monetary loss schedule used in our previous analysis, assuming catastrophic degradation.

Even when there is a string of devices, we are able to remove the loss rate from the integral for catastrophic failure mode, because a failure of any device constitutes a failure of the total string. The differential loss for a string of N identical devices is

$$\frac{dL}{rt} \Delta t = \Delta t \, R(t) \, N \, F(t)$$

when the probability of a single catastrophic failure is much less than unity. The total reliability loss for a string of N devices is

$$L = N \int_0^{t_s} R(t) \, F(t) \, dt$$

that is N times the loss associated with a single device -- the same formula employed in our initial analysis.[8,9]

Even with gradual degradation, if the loss schedule can be represented as a single step function, the calculation of the system loss for a single device is the same as for catastrophic degradation. If we have more than a single

step in our loss schedule or more than one device we cannot use the catastrophic formulation directly.

We assume that an appropriate loss rate will be supplied. It is our responsibility to combine this loss rate with the cumulative gain distribution as a function of time, $\mathscr{F}(g|t)$. The gradual gain cff is estimated from an aging test. If the sample of devices aged is very large, we can reasonably assume that the gradual gain cff can be determined exactly. If the aging sample size is not large, which will be the case for power GaAs FETs because of large unit device cost and expensive testing required, we will not know the gradual degradation cff exactly but can only estimate. The estimate of the derived cff will be obtained by assuming certain properties of the gradual failure cff and using statistical inference to obtain the appropriate estimate of this cff, $\overline{\mathscr{F}(g|t)}$.

We will now suggest a method of processing the results from an accelerated aging test in which the devices gradually degraded. The accelerated test consists of aging n devices distributed between several elevated temperatures. Each device is maintained at a constant elevated temperature and the time required for the gain to degrade a specified level is determined. This is the same situation described in Section II, but we will now process the result recognizing that the devices gradually degraded and did not fail catastrophically.

The above results will be analyzed under the following assumptions:

1. The failure time at a constant temperature and applied electrical is log normal.

2. The logarithmic variance for a given gain degradation is independent of temperature.

3. The median failure time for a given gain degradation follows an Arrhenius dependence.

4. The best estimate of the cumulative failure times distribution to reach a given gain degradation is the Student-t analysis.

5. The median gain decreases in a linear manner with time.

6. The logarithmic variance is independent of degradation level.

7. The best estimate of the device reliability is the loss function

$$L = \int_o^{t_s} \left[ \int_o^1 \left( \frac{d\mathscr{L}(t,g)}{dg} \right) \; \overline{\mathscr{F}(g\,|\,t)} \; dg \right] dt$$

The first four assumptions are the same as those used in the analysis of catastrophic degradation in Section II. The fifth assumption, regarding the time dependence of gradual degradation, is the same dependence discussed in the previous section. If past experience had indicated that the gain degradation proceeded as some other power of time different than linear, we would have used an approach similar to the one we use to treat linear degradation.

The answer to our immediate problem is an estimate of the cumulative gain degradation as a function of operating time $\overline{\mathscr{F}(g\,|\,t)}$. Following our previous analysis of catstrophic degradation, we estimate the cumulative failure time distribution from the Student-t analysis, which gives

$$P = \left\{ \ell n t_{n+1}(g) < \overline{\ell n \tau_o(g)} + \overline{\Delta E} \; Z_N + t_{n-2} \left[ \overline{F(t\,|\,g)} \right] \hat{\sigma} (\frac{\sigma_u}{\sigma}) \right\} = \overline{F(t\,|\,g)}$$

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This is the same expression we used previously, except we now explicitly indicate that $\tau_0(g)$, $F(t|g)$, and $t_{n+1}(g)$ are dependent on an arbitrary assigned relative gain failure criterion, g.

The activation energy is not dependent on the gain failure criterion. The activation energy is operationally defined as

$$\frac{\tau_{M1}(g)}{\tau_{M2}(g)} = \exp\left[\frac{\Delta E}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

Where $\tau_{Mi}(g)$ is the median failure time to reach a gain degradation of g when operated at $T_i$. For a different failure criterion we write

$$\frac{\tau_{M1}(g')}{\tau_{M2}(g')} = \exp\left[\frac{\Delta E'}{k}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right]$$

But $\tau_{Mi}(g)$ and $\tau_{Mi}(g')$ at $T_i$ are related as

$$\frac{\tau_{Mi}(g)}{\tau_{Mi}(g')} = \frac{1 - g}{1 - g'}$$

which gives

$$\frac{\tau_{M1}(g)}{\tau_{M2}(g)} = \frac{\tau_{M1}(g')}{\tau_{M2}(g')}$$

and proves that the activation energy is independent of the failure criterion used. By a similar argument the Arrhenius pre-exponential factor depends on the relative gain failure criterion as

$$\frac{\tau_o(g)}{\tau_o(g')} = \frac{1 - g}{1 - g'}$$

According to assumptions 2 and 6, logarithmic standard deviation of the failure times is independent of both temperature and the relative gain degradation criterion. Therefore, both $\hat{\sigma}$ and $(\sigma_u/\sigma)$ will be independent of temperature and the failure criterion.

The cumulative failure time distribution, $\overline{F(t|g)}$, estimated from the Student-t analysis for various failure criteria, consists of parallel curves (when plotted on normal probability paper) displaced along the log t axis by the ratio

$$\ln[\tau_o(g)/\tau_o(g')] = \ln\left[\frac{1 - g}{1 - g'}\right]$$

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We can therefore use the calculated $F(t|g)$ to find any other $F(t|g')$ and thereby $\mathscr{F}(g'|t)$. The above reasoning is expressed as

$$P\left\{\ell n t_{n+1} < \ell n\left[\left(\frac{1-g'}{1-g}\right)\overline{\tau_o(g')}\right] + \overline{\Delta E}\, Z_N - t_{n-2}\left[\overline{F(t|g')}\right]\hat{\sigma}\left(\frac{\sigma_u}{\sigma}\right)\right\} = \overline{\mathscr{F}(g|t_{n+1})}$$

where $t_{n+1}$ corresponds to the operational usage time for the $n + 1$ (i.e., unaged) device.

Having determined $\overline{\mathscr{F}(g|t_{n+1})}$, we can now determine the reliability loss if we are provided with the applicable loss schedule.

The above analysis is incomplete in that it did not consider the measurement error associated with determining the failure times to reach an arbitrary failure criterion. We hope that this important issue will be addressed in the near future.

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